Modified from photo by M.G. Rupert

NATIONAL WATER-QUALITY ASSESSMENT PROGRAM – NAWQA

Improvements to the DRASTIC Ground-Water Vulnerability Mapping Method

INTRODUCTION

Ground-water vulnerability maps are designed to show areas of greatest potential for ground-water contamination on the basis of hydrogeologic and anthropogenic (human) factors. The maps are developed by using computer mapping hardware and software called a geographic information system (GIS) to combine data layers such as land use, soils, and depth to water. Usually, ground-water vulnerability is determined by assigning point ratings to the individual data layers and then adding the point ratings together when those layers are combined into a vulnerability map.

Probably the most widely used ground-water vulnerability mapping method is **DRASTIC**, named for the seven factors considered in the method: **D**epth to water, net **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of vadose zone media, and hydraulic **C**onductivity of the aquifer (Aller and others, 1985, p. iv). The DRASTIC method has been used to develop ground-water vulnerability maps in many parts of the Nation; however, the effectiveness of the method has met with mixed success (Koterba and others, 1993, p. 513; U.S. Environmental Protection Agency, 1993; Barbash and Resek, 1996; Rupert, 1997). DRASTIC maps usually are not calibrated to measured contaminant concentrations.

The DRASTIC ground-water vulnerability mapping method was improved by calibrating the point rating scheme to measured nitrite plus nitrate as nitrogen (NO_2+NO_3-N)

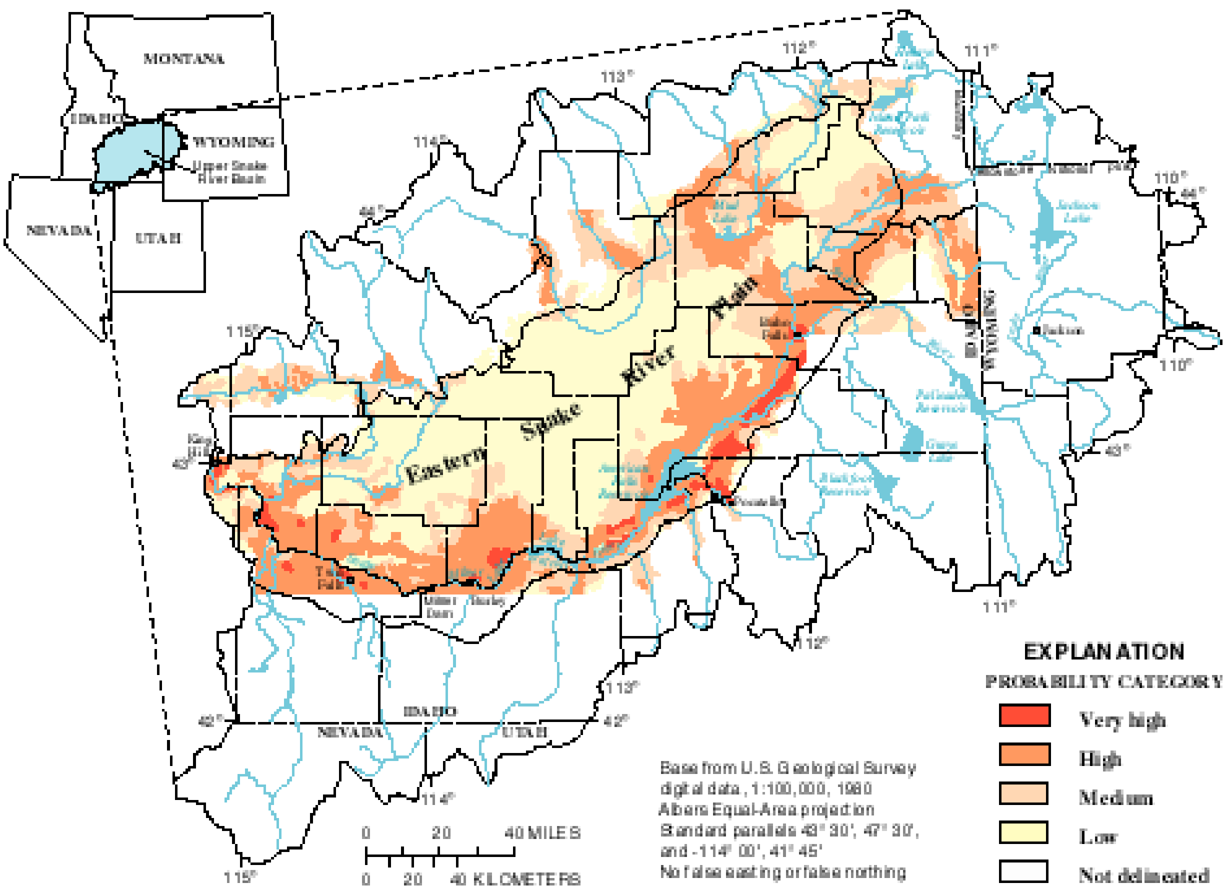


Figure 1. Probability of ground-water contamination by dissolved nitrite plus nitrate as nitrogen, eastern Snake River Plain, Idaho.

concentrations in ground water on the basis of statistical correlations between $NO_2 + NO_3{-}N$ concentrations and land use, soils, and depth to water (Rupert, 1997). This report describes the calibration method developed by Rupert and summarizes the improvements in results of this method over those of the uncalibrated DRASTIC method applied by Rupert and others (1991) in the eastern Snake River Plain, Idaho.

DESCRIPTION OF STUDY AREA

The 35,800-square-mile upper Snake River Basin extends from western Wyoming to south-central Idaho (fig. 1). About 50 percent of the upper Snake River Basin is forest and rangeland, about 30 percent is irrigated agricultural land, and the remaining area is barren. Most of the 2.3 million acres of irrigated land is near the Snake River and near the mouths of tributary basins. Most cities and industrial centers are adjacent to the Snake River. Major dams and lakes in the basin store about 4.4 million acre-feet of water for irrigation of more than 1 million acres annually.

The 10,800-square-mile eastern Snake River Plain (fig. 1) is about 60 miles wide and 170 miles long. The plain is underlain by a series of highly vesicular and fractured olivine basalt flows of Quaternary age, each averaging 20 to 25 feet in thickness; total thickness is as much as 5,000 feet (Whitehead, 1992). These basalt flows are highly transmissive to ground water and supply most of the drinking water in the study area. Sedimentary rocks of Paleozoic age and volcanic rocks of Tertiary age predominate north, east, and south of the plain. Sedimentary rocks of Quaternary and Tertiary ages and, to a lesser extent, volcanic rocks of Quaternary and Tertiary ages predominate in the mountain valleys.

Table 1. Rating scheme for probability of ground-water contamination by dissolved nitrite plus nitrate as nitrogen, eastern Snake River Plain

Land use	Rating (points)
Urban	3
Irrigated agriculture	2
Rangeland	1
Dryland agriculture	1
Forest	1
Soil drainage	**Rating (points)**
Excessive	4
Well	3
Moderate	2
Poor	1
Depth to water	**Rating (points)**
0 to 300 feet	2
301 to 900 feet	1
Contamination probability	**Resultant probability rating (points)**
Very high	8
High	7
Medium	6
Low	4 to 5

DEVELOPMENT OF THE UNCALIBRATED DRASTIC VULNERABILITY MAP IN IDAHO

The first published map of ground-water vulnerability in Idaho was developed by Rupert and others (1991), who used a modified form of the DRASTIC method. Three of the seven DRASTIC factors—depth to water, net recharge (land use), and soil media—were used because they were believed to be the most important factors with respect to ground-water vulnerability, and because they were the most readily accessible data. Land use was used as a surrogate for net recharge because irrigated agricultural areas provide the largest amount of re-charge in southern Idaho. The point ratings were different from those used in the DRASTIC method, but they were determined in the same manner; a committee used their best professional judgment to determine the point ratings. The resultant map was termed "relative ground-water vulnerability" because the vulnerability ratings (low, medium, high, and very high) were determined relative to each other and were not based on measured ground-water quality data (Rupert and others, 1991).

DEVELOPMENT OF THE NEW CALIBRATED PROBABILITY MAP

The vulnerability map developed using the uncalibrated DRASTIC method (Rupert and others, 1991) was improved by calibrating the point rating scheme on the basis of correlations of $NO_2 + NO_3{-}N$ concentrations in ground water with land-use, soils, and depth-to-water data; nonparametric statistics and a GIS were used to quantify the relations. On the basis of the relations, a point rating scheme was developed that classifies areas according to their potential for ground-water contamination by $NO_2 + NO_3{-}N$. That point rating scheme then was entered into the GIS, and the probability map was produced.

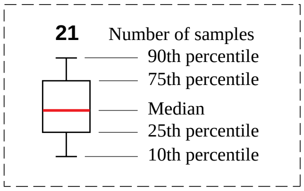
The Wilcoxon rank-sum nonparametric statistical test (Ott, 1993, p. 279, 793) was used to correlate $NO_2 + NO_3{-}N$ concentrations with land-use, soils, and depth-to-water data. This test determines whether differences in $NO_2 + NO_3{-}N$ concentrations are statistically significant between the various data groups, for example, whether $NO_2 + NO_3{-}N$ concentrations in ground water in irrigated agricultural areas are statistically different from concentrations in rangeland areas. The test calculates a p-value; if the resulting p-value is less than 0.05, then the data sets are significantly different at the 95-percent confidence level. If the p-value is less than 0.01, then the data sets are significantly different at the 99-percent confidence level. For this report, the 95-percent confidence level was used as the cutoff value for determining whether differences between data sets were statistically significant.

Ground-Water Quality Data Used for Calibration

The $NO_2 + NO_3{-}N$ ground-water quality data used for calibration of the probability map were collected for the Idaho Statewide Ground Water Monitoring Program (ISGWMP), which is a cooperative program between the U.S. Geological Survey (USGS) and the Idaho Department of Water Resources (Idaho Department of Water Resources, 1991; Neely and Crockett, 1992; Neely, 1994; Crockett, 1995). The ISGWMP data were ideal for calibration of the map because wells were selected in a random manner, all wells were sampled using the same techniques, all samples were analyzed by the same laboratory, and all data were stored consistently in a single

EXPLANATION FOR BOXPLOTS

(Figures 2, 3, 4, 5, 6, 7)



Lines above boxplots in the following figures indicate results of individual Wilcoxon rank-sum tests between each category. Resulting p-values less than or equal to 0.05 (concentrations are different at a 95-percent or greater confidence level) are labeled on solid red lines. Result-ing p-values greater than 0.05 (concentrations are not different at a 95-percent confidence level) are labeled on dashed black lines. The 10th and 90th percentiles are not shown on boxplots if fewer than 10 wells were sampled.

data base. Data collected from 726 wells during calendar years 1991–94 were used for calibration.

Land-Use Probability Ratings

Land-use data for Idaho were obtained from the Idaho Department of Water Resources, which combined the data from three sources: a map denoting vegetation types; a map differentiating between sprinkler- and gravity-fed irrigation methods; and a map differentiating dryland agriculture from irrigated agriculture (Rupert and others, 1991, p. 12). Land-use data were not available for Wyoming, Utah, or Nevada.

NO_2+NO_3–N concentrations in ground water in irrigated agriculture and urban areas were significantly higher than in rangeland, dryland agriculture, and forest areas (fig. 2). In addition, NO_2+NO_3–N concentrations in urban areas were significantly higher than in irrigated agriculture areas, but the small number of wells sampled in urban areas might have biased this result. These results are similar to those reported by Rupert (1994, p. 29).

Urban areas were assigned a probability rating of 3 (table 1) because NO_2+NO_3–N concentrations in ground water in urban areas were higher than in all other land-use areas. Irrigated agriculture areas were assigned a probability rating of 2 because NO_2+NO_3–N concentrations in irrigated areas were significantly higher than in other land-use areas except urban. Rangeland, dryland agriculture, and forest areas were combined and assigned a probability rating of 1 because NO_2+NO_3–N concentrations were lowest in those areas and differences in concentrations were not statistically significant.

Soil Probability Ratings

Soil data were obtained from the State Soil Geographic Data Base (STATSGO), developed by the U.S. Natural Resource Conservation Service (U.S. Department of Agriculture, 1991). Soil criteria considered were clay content, drainage, hydrologic group, percentage of organic matter, permeability, and Unified Soil Classification ratings. STATSGO soil data were aggregated from many large-scale soil surveys

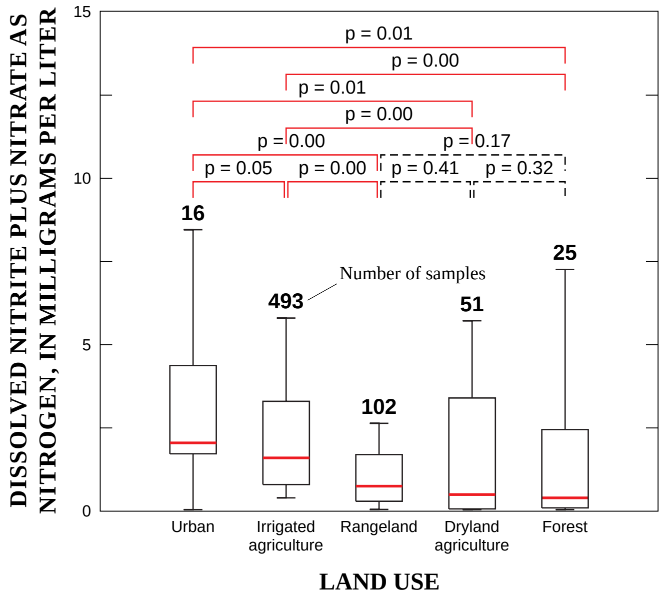


Figure 2. Correlations between concentrations of dissolved nitrite plus nitrate as nitrogen and land use, upper Snake River Basin, 1991–94.

(1:12,000 to 1:62,500) into one large data base at an approximate scale of 1:250,000 (U.S. Department of Agriculture, 1991, p. 1, 2).

NO_2+NO_3–N concentrations and soil drainage were the most strongly correlated of the soil criteria examined (fig. 3). Although the relations are not illustrated, NO_2+NO_3–N concentrations also increased significantly with decreasing amounts of clay and decreasing amounts of organic matter. Concentrations increased with increasing amounts of sand

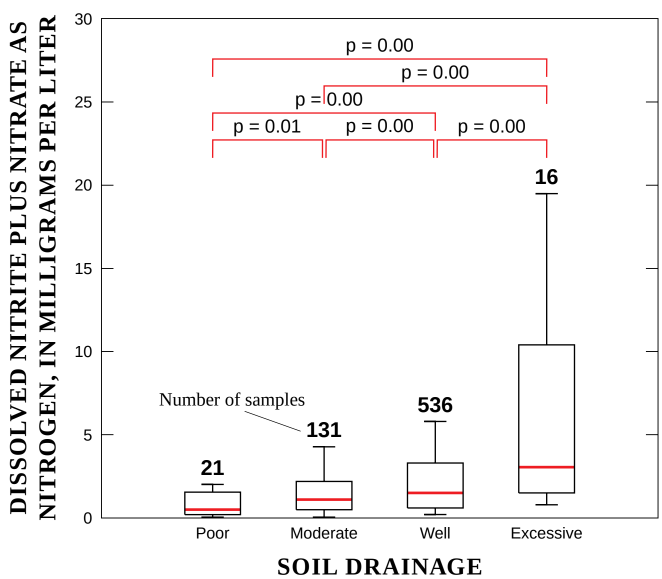


Figure 3. Correlations between concentrations of dissolved nitrite plus nitrate as nitrogen in ground water and STATSGO soil drainage categories, upper Snake River Basin, 1991–94. [STATSGO, State Soil Geographic Data Base (U.S. Department of Agriculture, 1991)]

and gravel, as represented by the Unified Soil Classification ratings. Surprisingly, soil permeability and hydrologic group were not correlated with NO_2+NO_3-N concentrations. Soil permeability is an estimate of how much water can pass through a saturated soil and commonly is measured on disturbed soil samples in a laboratory environment. The lack of correlation between NO_2+NO_3-N concentrations and soil permeability is probably because secondary soil features such as desiccation cracks and root pores are not included in the permeability rating, and important criteria such as clay content and organic matter content also are not accounted for. Soil drainage denotes the frequency and duration of wet periods of the soil (U.S. Department of Agriculture, 1993, p. 98). Soils with poor drainage typically are saturated with water and can have chemically reducing (anaerobic) conditions. Reducing conditions can lead to denitrification that can, in turn, minimize NO_2+NO_3-N concentrations. Correlations with soil drainage probably reflect these processes.

Differences in NO_2+NO_3-N concentrations between all soil drainage categories were statistically significant, so each soil drainage category was assigned a different point rating. Excessively drained soils were assigned a probability rating of 4, well-drained soils were assigned a rating of 3, moderately drained soils were assigned a rating of 2, and poorly drained soils were assigned a rating of 1 (table 1).

Depth-to-Water Probability Ratings

Depth to first-encountered ground water in the eastern Snake River Plain was mapped by Maupin (1992), who divided depth to water into five categories: 0 to 100 feet, 101 to 300 feet, 301 to 600 feet, 601 to 900 feet, and greater than 900 feet. The differences in NO_2+NO_3-N concentrations in ground-water samples from depths of 0 to 300 feet and from 301 to 900 feet were statistically significant ($p<0.05$, fig. 4). However, the differences in concentrations in first-encountered water from depths of 0 to 100 feet and 101 to 300 feet, or from depths of 301 to 600 feet and 601 to 900 feet were not significant ($p>0.05$). Because differences in NO_2+NO_3-N concentrations were not significant, depth to first-encountered water categories of 0 to 100 feet and 101 to 300 feet were combined and assigned a probability rating of 2 (table 1). Depth categories of 301 to 600 feet and 601 to 900 feet were combined and assigned a probability rating of 1.

GROUND-WATER PROBABILITY MAP

A map showing the potential for elevated NO_2+NO_3-N concentrations was developed (fig. 1) using the rating scheme shown in table 1. The map is termed a probability map instead of a vulnerability map because (1) the probability categories are based on the results of statistical comparisons of NO_2+NO_3-N in ground water, and (2) the term probability more clearly states what the maps portray; whether an area has a high or low relative probability for ground-water contamination by NO_2+NO_3-N.

Many different combinations of point rating schemes for depth to first-encountered ground water, land use, and soil drainage were evaluated. For example, a rating of 4 points instead of 2 points was tried for depth to first-encountered ground water of 0 to 300 feet. The point rating scheme (table 1) that produced the lowest p-values was used in the final probability map. The final map produced good correlations with NO_2+NO_3-N; the largest p-value was 0.01, and five of the p-values were less than 0.01, which suggests statistically significant differences (greater than 99-percent confidence level) of NO_2+NO_3-N between the probability categories (fig. 5).

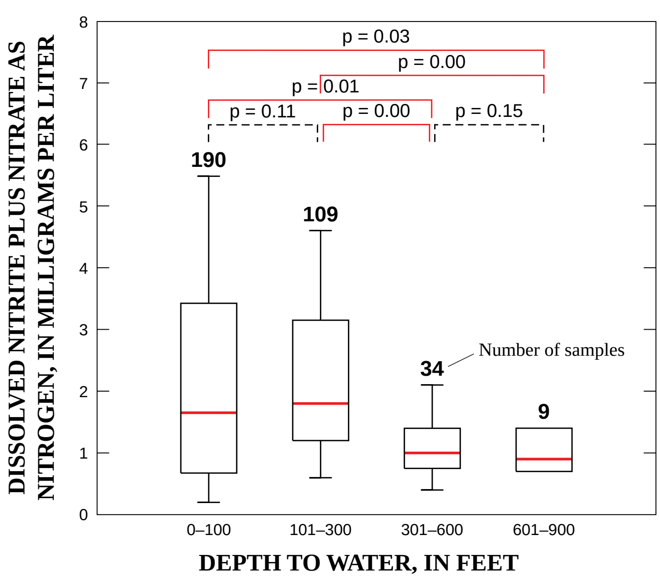


Figure 4. Correlations between concentrations of dissolved nitrite plus nitrate as nitrogen and depth to first-encountered ground water, eastern Snake River Plain, 1991–94.

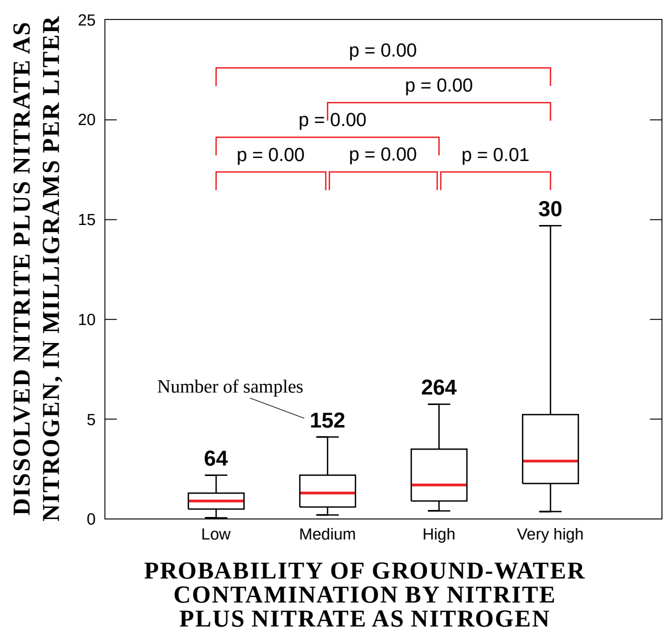


Figure 5. Correlations between concentrations of dissolved nitrite plus nitrate as nitrogen collected for the Idaho Statewide Ground Water Monitoring Program and contamination probability, eastern Snake River Plain, 1991–94.

COMPARISON OF NEW PROBABILITY MAP WITH OLD VULNERABILITY MAP

The effectiveness of the ground-water probability map to predict elevated NO_2+NO_3–N concentrations in ground water was compared with the effectiveness of the relative ground-water vulnerability map produced using the uncalibrated DRASTIC method (Rupert and others, 1991). Comparisons were made by correlating both maps with an independent set of NO_2+NO_3–N data, which were retrieved from the USGS data base in Boise for calendar years 1980–91. All data collected by the ISGWMP were excluded from this data set. A direct comparison was possible because the same land-use, soil, and depth-to-water data layers were used to develop both maps.

The relative ground-water vulnerability map produced by Rupert and others (1991) correlated poorly with NO_2+NO_3–N concentrations in ground water (fig. 6). The differences in NO_2+NO_3–N concentrations in the low and medium, low and very high, and high and very high relative ground-water vulnerability categories were not statistically significant ($p>0.05$). Mean and median NO_2+NO_3–N concentrations in the very high vulnerability category were lower than concentrations in the high category. The median NO_2+NO_3–N concentration in the medium vulnerability category was lower than in the low category. Results of this correlation show that the relative vulnerability map produced with the uncalibrated DRASTIC method is not effective in predicting elevated NO_2+NO_3–N concentrations in ground water.

The probability map produced by Rupert (1997) correlated well with NO_2+NO_3–N concentrations in ground water (fig. 7). The mean and median NO_2+NO_3–N concentrations increased in all categories as the probability rating increased.

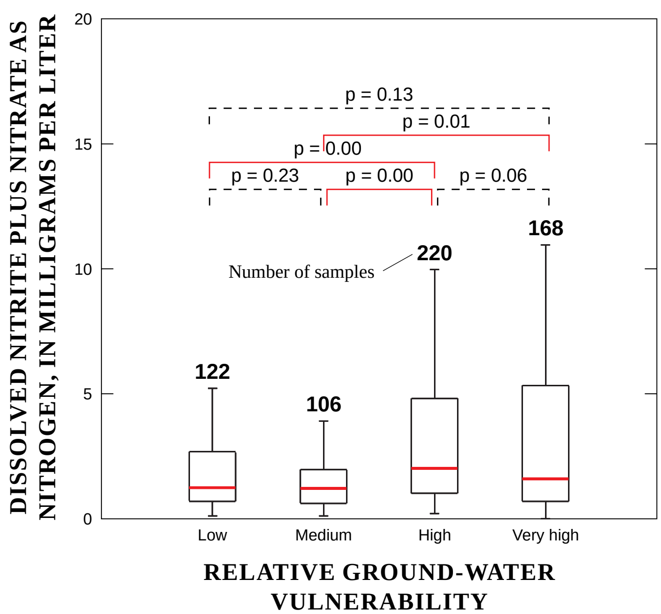


Figure 6. Correlations between concentrations of dissolved nitrite plus nitrate as nitrogen from an independent data set and relative ground-water vulnerability ratings of Rupert and others (1991), eastern Snake River Plain, 1980–91.

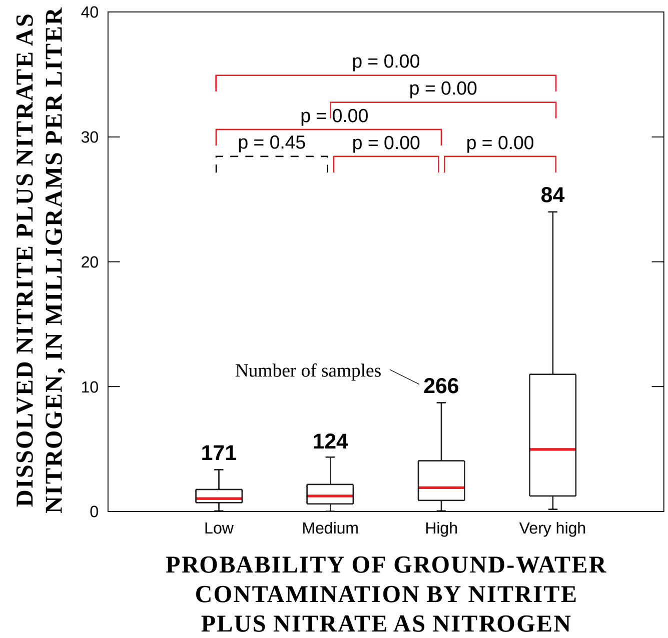


Figure 7. Correlations between concentrations of dissolved nitrite plus nitrate as nitrogen from an independent data set and contamination probability, eastern Snake River Plain, 1980–91.

Differences in NO_2+NO_3–N concentrations between all probability categories except between low and medium were statistically significant ($p<0.05$). Even though the difference in concentrations between the low and medium probability categories was not significant, the mean and median NO_2+NO_3–N concentrations were higher in the medium category than in the low category. Results of this correlation demonstrate that the probability map is effective in predicting elevated NO_2+NO_3–N concentrations in ground water.

CONCLUSIONS

The effectiveness of vulnerability and probability maps can be improved by calibrating the point ratings on the basis of the results of statistical correlations between ground-water quality and hydrogeologic and anthropogenic factors. Determining vulnerability point ratings on the basis of best professional judgment, as generally is done with the uncalibrated DRASTIC method, and was done in the Idaho area by Rupert and others (1991), is not as effective.

The most significant weakness of the relative vulnerability map developed using the uncalibrated DRASTIC method (Rupert and others, 1991) is that soil permeability was the primary soil factor, similar to other uncalibrated DRASTIC maps. There was no correlation between NO_2+NO_3–N and soil permeability, but there was a strong correlation with soil drainage types, presumably because soil drainage is a better indicator of nitrate leaching conditions. Calibration of the probability maps with ground-water quality is the most effective way to determine which hydrogeologic and anthropogenic factors are related to the chemical compound of interest.

The probability map was calibrated only for NO_2+NO_3–N and may not be effective for other compounds. Calibrated probability maps developed using the logistic regression statistical method (Rupert, 1998) demonstrated that land use, precipitation, soil hydrologic group, and well depth were significantly correlated with atrazine/desethyl-atrazine detections in ground water. In contrast, depth to water, land use, and soil drainage likely were significantly correlated with elevated NO_2+NO_3-N concentrations. The differences between atrazine/desethyl-atrazine and NO_2+NO_3-N relations likely were due to differences in chemical behavior of these compounds in the environment and possibly to differences in the extent of use and rates of their application.

USES OF GROUND-WATER PROBABILITY MAPS

Ground-water probability maps can be used by resource protection agencies to focus pollution prevention programs on areas of greatest concern and to focus ground-water sampling programs on areas of greatest potential for contamination. Organizations and programs that might benefit from such maps include the agri-chemical industry; agricultural producers; Native American tribes; county and city governments; planning and zoning commissions; education programs for applicators; and State programs related to Wellhead Protection, Drinking Water, Home-A-Syst, and Best Management Plans (BMPs).

THE NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

Funding and resources for this report were provided by the USGS National Water-Quality Assessment Program. Long-term goals of this program are to describe the status and trends of the quality of a large, representative part of the Nation's surface- and ground-water resources and to provide a sound, scientific understanding of the primary natural and human factors affecting the quality of these resources. In meeting these goals, the program will produce a wealth of water-quality information that will be useful to policy makers and managers at national, State, and local levels. The upper Snake River Basin was among the first 20 study units that began this water-quality assessment.

—Michael G. Rupert

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Additional information on the National Water-Quality Assessment Program and other U.S. Geological Survey programs can be accessed on the World Wide Web at

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Data and information compiled for Upper Snake River Basin study unit activities can be accessed on the World Wide Web at

http://wwwidaho.wr.usgs.gov/nawqa/usnk_home.html